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Assessment of Transient Stability Support for Electric Vehicle Integration

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Abstract—Gradual escalation of electric vehicle (EV) penetration in modern power systems requires increasing support for EV charging. This additional demand represents a significant proportion of daily electric load which requires greater or flexible generation and transmission and poses challenges to system security and stability. This paper considers the impact of EV integration on transient stability by using an equivalent model of the Northern Ireland (NI) power system. The paper proposes an AC/DC converter-based EV aggregator model with two typical EV connections. A range of typical faults is investigated and discussed through simulation. The critical clearing time (CCT) and transient stability margin are used to assess transient stability on the NI system. Simulation results indicate that in order to achieve and sustain 2020 EV integration targets and guarantee adequate transient stability, asset support and network reinforcement will be required and these outcomes are described in the paper.

Index Terms—electric vehicle (EV), power system, transient stability, critical clearing time (CCT), transient stability margin

I. INTRODUCTION

The UK government has made numerous efforts to reduce greenhouse gas (GHG) emission including transportation electrification. The UK government's strategy for ultra-low emission vehicles (ULEVs) establishes an unprecedented long-term commitment to advance transition to low-emission vehicles. The UK Office for Low Emission Vehicles (OLEV) continues to coordinate government support and organizes practical steps needed to position the UK at the forefront of this area [1]. It is anticipated that the UK will have 1.2 million battery electric vehicles (BEV) and 0.35 million plug-in hybrid electric vehicles (PHEV) by 2020; and, 3.3 million BEVs and 7.9 million PHEVs by 2030, [2]. In June 2015, there were approximately 37.3 million domestic road vehicles in the UK, of which, 35,200 vehicles were EVs [3]. In Northern Ireland (NI) in particular, since April 2011, a comprehensive network of 334 public charge points has been installed for electric vehicles (EVs). The NI EV network is owned and operated by the Electricity Supply Board (ESB)

Group through its ESB car business. NI is a comparatively small region (population of 1.7 million) with the number of EVs in NI increasing from 5 in 2011 to 750 in July 2015 [4]. In comparison with the UK population (NI 2.9% of the UK) [5] and vehicle proportions (NI 3% of the UK) [6], it is estimated that there will be around 36,000 BEVs and 10,500 PHEVs in NI by 2020.

According National Grid, in a published *Future Energy Scenarios* document, [7] the total EV energy demand by 2020 will be 0.32% of the total UK annual electric demand. However, EV charging demand during mid-winter will peak at almost 26.6%, which represents a significant load. Moreover, in a typical UK mid-winter, the average electricity customer currently consumes 13 kWh, but the expected average EV charge consumption will be approximately 6.3kWh per day, which means an increase of almost 50% in domestic consumption [8]. Although the overall forecast level of EV uptake by 2020 is not expected to represent an issue for the National Grid, EVs in particular locations will require local grid-reinforcement [9]. Therefore in terms of power systems, it is of significant importance to analyze the impact of large-scale EV integration on stability.

In the broad context of power systems, transient stability refers to the ability of AC generators to remain in synchronous operation following a large disturbance. Maintaining transient stability is one of the most important priorities in power systems and is usually studied on a *first-swing* rather than a *multi-swing* basis. The critical clearing time (CCT) is usually adopted to evaluate transient stability [10]. Three methods are typically used to determine the CCT, which are extended equal-area criteria (EEAC), transient energy function (TEF), and time-domain simulation [10]. Since EEAC has limited accuracy [11] and it is difficult to construct an appropriate energy function [12], the time-domain simulation method has been widely used in practice to obtain the CCT.

In published work to date, there are two major approaches in the study of power system transient stability with large-scale EV integration. The first approach considers EV

charging demand as an additional *block* in the system configuration while the power electronic converter is not included [13-14]. In this approach, transient stability retains its original definition and EV charging demand is integrated as part of the load. The second approach considers inclusion of power electronic converters whereby an EV aggregator model [15-20] is integrated and used during fault conditions [21-22]. In this latter approach, transient stability is defined as the capability of the EV aggregator – which is considered as a virtual power plant (VPP) – to remain in synchronous operation with the bulk power system and maintain the voltage level (and stability) within acceptable limits following large disturbances and typical faults. A large disturbance usually include short-circuit faults [21], loss of load and loss of generation [10]. However, typical faults for EV provision are not extensively classified. Since EV charging demand is usually obtained from discrete, time-domain values, a change in EV power demand, which can be regarded as a small step-disturbance, should be well performed and excluded from the typical faults [22].

At present, there is limited published work on the impact of large-scale EV integration on transient stability. It is believed this is due to: 1) a perceived misunderstanding of the behavior of EVs – the common assumption being that they *behave* similar to energy storage systems (ESS); and 2) a lack of real and large-scale EV aggregators. Although optimal EV charging and discharging profiles are usually obtained hourly or half-hourly while transient stability simulations are up to 10 seconds in duration, in each time interval EV charging and discharging profiles remain constant, which reinforces a comparative similarity to an ESS. However, since EV charging demand is controllable and variable in each time interval, EVs can operate unlike ESSs [23]. Moreover, the lack of real, large-scale EV aggregators also limits any study in terms of practical verification, which limits model simulations to theoretical study.

This paper considers transient stability constraints and has used an equivalent model of the NI power system to assess capability and support for EV integration in 2020. Section II introduces an AC/DC converter-based EV aggregator model, followed in Section III by a brief discussion of two EV connections and typical faults. Section IV provides a definition of transient stability margin with EV integration and Section V presents a case study. Section VI concludes the findings of this paper.

II. AC/DC CONVERTER-BASED EV AGGREGATOR MODEL

A practical approach which considers external characteristic modelling is applied to construct an AC/DC converter-based EV aggregator model [17-20]. In comparison to previous work [17-18], the proposed model has fewer state variables and considers both the AC side (system) voltage and DC side (EV) voltage and a P-Q control algorithm. The equivalent model is shown in Figure 1.

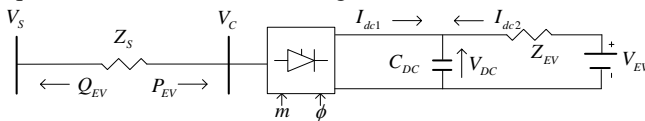


Figure 1. Equivalent AC/DC converter-based EV model

In Figure 1, Node S and Node C are the EV connection nodes with the power system and AC side bus of EV aggregator, respectively. $V_S \angle \delta_S$ and $V_C \angle \delta_C$ are the voltages of each node. V_{EV} is the charging and discharging voltage and V_{DC} is the voltage of the DC side bus. P_{EV} is the EV charging power receiving from the systems and Q_{EV} is the reactive power sending to the systems by the EV aggregator. The EV is connected to a power systems through a step-down transformer and $Z_S = jX_S$. Z_{EV} refers to the equivalent resistance of power loss inside the EV aggregator, and thus $Z_{EV} = R_{EV}$. m and ϕ are the modulation ratio and phase of the equivalent converter and $\phi = \delta_S - \delta_C$ assuming V_S is leading V_C . The **bold** letters refer to a phasor. In this paper, a voltage control converter with the pulse width modulation (PWM) strategy has been adopted. Therefore, the dynamic equations of the proposed model are shown as follows:

$$\begin{cases} \dot{V}_{DC} = (I_{dc1} + I_{dc2})/C_{DC} \\ m = m_r + (K_{pac} + K_{ac}/s)(V_{Sr} - V_S) \\ \phi = \phi_r + (K_{pdc} + K_{dc}/s)(V_{DCr} - V_{DC}) \end{cases} \quad (1)$$

where K_{pac} , K_{ac} , K_{pdc} , and K_{dc} are the gains of the AC and DC voltage PI controller, respectively. Subscript r refers the reference value. The voltage at AC side bus is,

$$V_C = mkV_{DC} \angle \delta_C = mkV_{DC} \angle \delta_S - \phi \quad (2)$$

where k is a constant dependent on the converter structure.

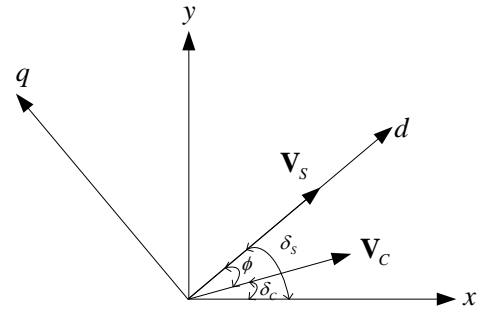


Figure 2. Phasor diagram in the d-q coordinate of the converter based unit

From Figure 1 and 2, $V_C = V_S - jX_S I_S$. Hence,

$$\begin{cases} I_{Sd} = mkV_{DC} \sin \phi / X_S \\ I_{Sq} = (mkV_{DC} \cos \phi - V_S) / X_S \end{cases} \quad (3)$$

Since, $V_{DC} I_{dc1} = I_{Sd} V_{Cd} + I_{Sq} V_{Cq} = I_{Sd} mkV_{DC} \cos \phi - I_{Sq} mkV_{DC} \sin \phi$,

$$I_{dc1} = I_{Sd} mk \cos \phi - I_{Sq} mk \sin \phi \quad (4)$$

Taking into account

$$I_{dc2} = (V_{EV} - V_{DC}) / R_{EV} \quad (5)$$

Equations (1), (3), (4), and (5) render the full mathematical expression of the proposed model. Based on this model, the AC-side voltage, DC-side voltage and control of the model, as well as the active and reactive power can thus be expressed.

III. EV CONNECTIONS AND TYPICAL FAULTS

A. EV connections

Large-scale EV aggregators are usually connected in medium-voltage (MV) [19] or low-voltage (LV) [24] distribution networks. Two EV connection types are proposed according to the system structures, as shown in Figure 3.

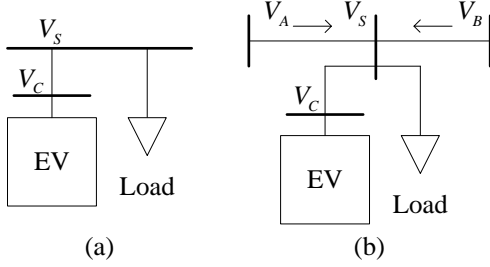


Figure 3. EV connections

In Figure 3, the block is a representative of EV model excluding V_S , V_C and Z_S in Figure 3 (a) shows EV connection at the receiving end of a radial network, while Figure 3 (b) shows EV connection at any node in a bulk power system. The load in Figure 3 can be zero if the EV aggregator is configured and connected with an independent node. Figure 3 (a) can be regarded as a single-load infinite-bus (SLIB) connection and Figure 3 (b) as a general connection.

B. Typical faults

With EV integration, typical faults include short-circuit faults and loss of load. The faults can be generally categorized as occurring on the system side, AC side of the EV aggregator and at the load side. It should be noted that in this study the detailed topology of EV aggregator is not specified, so faults inside the EV aggregator and the faults at the charger (EV side) are not considered. Typical faults are defined as:

- SLIB type

F1: Three-phase to ground fault at Node S (system side);

F2: Three-phase to ground fault at Node C (AC side);

- General type

F3: Three-phase to ground fault at Node B (system side);

F4: Three-phase to ground fault at Node C (AC side);

F5: Loss of load (load side).

A load-side fault in a SLIB is not included because Node S is an infinite bus and the load can be regarded as constant.

IV. TRANSIENT STABILITY MARGIN WITH EV INTEGRATION

Assuming the bulk power system is a virtual generator, EEAC is applied to demonstrate the transient stability margin

with EV integration. A typical power-angle curve of P_{EV} over ϕ is given in Figure 4.

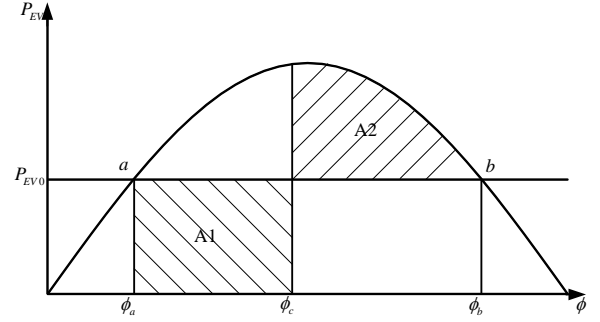


Figure 4. Power-angle curve of P_{EV} over ϕ

The transient stability margin is defined as the ratio of the deceleration area A2 over the acceleration area A1 under the same clearing time [11]. When the ratio is = 1, the area of A1 equals the area of A2. This is a critical point for transient stability. When the ratio is < 1, the system is transient unstable. When the ratio is > 1, the system is transient stable. Hence, with a larger ratio, a larger margin is obtained. From Figure 4 it is apparent that when P_{EV0} is large, A1 is comparatively large and A2 smaller at the same clearing time, meaning that the transient stability margin is smaller. In practice, the transient stability margin is calculated in (6),

$$\xi = (P_{EV \max} - P_{EV0}) / P_{EV \max} \times 100\% \quad (6)$$

where $P_{EV \max}$ is the maximum EV charging demand at a certain CCT, which creates the critical point for transient stability. With any EV integration, ξ is always < 1. The value of ξ is discussed as follows:

- 1) $0 < \xi < 1$ means the system is transient stable. The larger the value, the larger the margin;
- 2) $\xi = 0$ means the system is critical, transient stable. The deceleration area equals to the acceleration area;
- 3) $\xi < 0$ means the system is transient unstable. The actual EV charging demand P_{EV0} should be reduced.

V. CASE STUDY

A. NI system description

By 2020, it is expected there will be 67 nodes in the NI transmission system [25-28]. Based on the location of the 275 kV and 110 kV transmission bus-bars among 26 local regions, an equivalent network model is obtained, as shown in Figure 5. In this network, 3 regions, named *Ballymoney*, *Cookstown*, and *Moyle*, are integrated into other regions, since there is no 275 or 110 kV transmission grid in these regions. The other 23 regions are simplified as bus-bars and numbered from 1 to 23 in alphabetical order. 'To GB' and 'To IRE' refer to the interconnectors between NI and GB, and NI and Ireland. ☺

Figure 5. Simple equivalent NI system configuration

System characteristics and generation data in 2020 were obtained from [25-27] and load flow data from [28]. The load data, by region, were obtained from [29-30]. A Phillips-Heffron model [17] was adopted for the conventional generators and a 3rd order, doubly-fed induction generator (DFIG) model [31] was considered for wind clusters/farms. Data of the EV model are shown in Table I.

TABLE I. DATA OF EV MODEL

V_{Sr}	1	V_{DCr}	1	V_{EV}	1	V_{C0}	1.01
k	5	C_{DC}	1	X_S	0.1	R_{EV}	0.01
K_{pac}	0.2	K_{ac}	5	K_{pdc}	0.2	K_{dc}	5

B. Simulation approach and results

In this case, a power flow solution for the NI 2020 winter-maximum scenario was obtained, which then calculates the CCT of different faults without EV connections. An EV aggregator is considered to be connected, one by one in different regions. As EVs are connected, power flow solutions and the maximum EV demand, with the same CCT (of the same fault) in the same region, are calculated. Taking into account standard EV charging power ratings [23], reference EV demand levels are obtained and compared with the calculated results. The typical UK commuter EV charging profile [7] is considered as the optimized EV daily demand. The results are shown in Table II.

TABLE II. TRANSIENT STABILITY MARGIN AND MAX EV SUPPORT NUMBER

Region	All EV charging			UK commuter EV charging			Max EV demand (p.u.)	Max EV number	Nominal EV number
	@7kW	@22kW	@50kW	@7kW	@22kW	@50kW			
1. Antrim	1.8%	-208.5%	-601.2%	90.2%	69.1%	29.9%	0.1	1429	1402
2. Ards	84.5%	51.3%	-10.7%	98.5%	95.1%	88.9%	0.91	13000	2015
3. Armagh	-20.3%	-278.1%	-759.2%	88.0%	62.2%	14.1%	0.09	1286	1547
4. Ballymena	34.5%	-106.0%	-368.1%	93.4%	79.4%	53.2%	0.26	3714	2434
5. Banbridge	90.9%	71.5%	35.1%	99.1%	97.1%	93.5%	0.96	13714	1245
6. Belfast	-1506.8%	-4949.9%	-11377.0%	-60.7%	-405.0%	-1047.7%	0.035	429	6886
7. Carrickfergus	44.4%	-74.6%	-296.9%	94.4%	82.5%	60.3%	0.13	1857	1032
8. Castlereagh	-506.1%	-1805.0%	-4229.6%	39.4%	-90.5%	-333.0%	0.02	286	1732
9. Coleraine	27.0%	-129.3%	-421.1%	92.7%	77.1%	47.9%	0.14	2000	1459
10. Craigavon	44.9%	-73.1%	-293.5%	94.5%	82.7%	60.7%	0.31	4429	2440
11. Derry	-23.7%	-288.9%	-783.8%	87.6%	61.1%	11.6%	0.16	2286	2828
12. Down	84.6%	51.5%	-10.2%	98.5%	95.2%	89.0%	0.83	11857	1830
13. Dungannon	-955.6%	-3217.5%	-7439.8%	-5.6%	-231.8%	-654.0%	0.01	143	1508
14. Fermanagh	-470.1%	-1691.8%	-3972.3%	43.0%	-79.2%	-307.2%	0.02	286	1629
15. Larne	-118.9%	-587.9%	-1463.3%	78.1%	31.2%	-56.3%	0.04	571	1251
16. Limavady	-510.7%	-1819.2%	-4261.8%	38.9%	-91.9%	-336.2%	0.01	143	872
17. Lisburn	-205.5%	-860.0%	-2081.8%	69.5%	4.0%	-118.2%	0.07	1000	3055
18. Magherafelt	-1380.7%	-4553.6%	-10476.4%	-48.1%	-365.4%	-957.6%	0.01	143	2115
19. Newry and Mourne	54.6%	-42.8%	-224.6%	95.5%	85.7%	67.5%	0.4	5714	2596
20. Newtownabbey	-201.5%	-847.7%	-2053.9%	69.8%	5.2%	-115.4%	0.05	714	2154
21. North Down	-106.4%	-548.6%	-1374.1%	79.4%	35.1%	-47.4%	0.07	1000	2064
22. Omagh	63.1%	-16.1%	-163.8%	96.3%	88.4%	73.6%	0.26	3714	1372
23. Strabane	63.8%	-13.8%	-158.6%	96.4%	88.6%	74.1%	0.2	2857	1034

From Table II, it can be seen that the transient stability margin decreases with an increase in charging rating. Only the *Banbridge* system is sufficient to support all EV charging at the same time at any power level. Two regions can support all EV charging at the 7kW and 22kW levels and eight regions are able to support all EV charging at 7kW. In other regions, at various power levels, transient stability is not assured. Thus, in this scenario, a system operator should be aware that large numbers of EVs cannot be simultaneously connected and the total EV charging demand should be limited to less than the maximum value.

When optimal EV charging profile is considered, the results improve. In this case, there are ten regions that would not be able to maintain transient stability with EV charging at some or all power levels. Therefore it is proposed that standard charging (7kW) is recommended to all EV owners (in NI), based on statistical data and the outcomes and assumptions in this study. Only the total EV charging demand in *Belfast*, *Dungannon*, and *Magherafelt* should be assumed to be less than the maximum value. Moreover, it is recommended that grid-reinforcement with asset support and updates should be part of future planning to accommodate EV uptake in these regions. If standard charging is considered in

all regions, twelve regions would not be capable of accommodating a nominal number of EVs. At best, NI is able to support, at most, 72,571 EVs in 2020, which is 1.56 times the 2020 projection.

VI. CONCLUSIONS

This paper considers transient stability constraints in EV integrated power systems. An AC/DC converter-based EV aggregator model is proposed with two typical EV connections exemplified and typical faults discussed. A transient stability margin (with EV integration) is also introduced. The proposed model has been used for a transient stability analysis of the expected NI 2020 power system in order to EV support capability. Simulation results in this brief paper demonstrate a definite decrease in the transient stability margin with a consequent increase in EV charging ratings. Therefore, from this work, it is apparent that standard charging (of 7kW) is recommended to all EV owners (in NI) to maintain transient stability on the 2020 system. The paper has also concluded that the entire NI region is capable of supporting 1.56 times the projected 2020 EV provision; although grid and asset reinforcement will be required to reduce the impact on the stability margin (3 regions would be unable to maintain transient stability in the absence of system upgrading). This work provides timely and beneficial data for the transmission and distribution system operators (TSO, DSO) in terms of estimating the expected charging demand and anticipated grid and network-level investment required to accommodate large-scale EV integration (particularly for NI) in future power system planning.

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